

# Numerical Techniques and Cloud-Scale Processes for High-Resolution Models

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## LONG-TERM GOALS

The long-term goal of this project is to design and evaluate the components that will comprise a next generation mesoscale atmospheric model within the Coupled Ocean/Atmosphere Mesoscale Prediction System (COAMPS®<sup>1</sup>). It is anticipated that in order to meet future Navy requirements, next generation approaches to numerical techniques and physical parameterizations will be needed.

## OBJECTIVES

The objectives of this project involve the development, testing, and validation of: i) new numerical techniques such as advection schemes and time differencing methods, and ii) new methods for representing cloud-scale physical processes. Both of these objectives are tailored to address high-resolution applications for horizontal grid increments at 1 km or less.

## APPROACH

Our approach is to follow a methodical plan in the development and testing of a nonhydrostatic micro-scale modeling system that will leverage the existing COAMPS and new model prototypes. Our work on numerical methods will involve investigation of spatial and temporal discretization algorithms that are superior to the current generation leap-frog, second-order accurate numerical techniques presently employed in COAMPS and many other models; these new discretization methods will be developed and implemented. Our work on the physics for the next-generation COAMPS will feature the development of physical parameterizations specifically designed to represent cloud-scale processes operating on fine scales. A parameterization is proposed that properly represents the coupled nature between the turbulence and microphysics in droplet activation, evaporation, and auto-conversion processes for mesoscale and microscale models. Validation and evaluation of the modeling system will be performed using datasets of opportunity, particularly in regions of Navy significance.

## WORK COMPLETED

### *1. New lower boundary condition for the COAMPS dynamical core*

Over the past several years, a negative geopotential height bias has been apparent in the COAMPS model during wintertime months. This height bias was particularly apparent in mid-latitude regions such as the FNMOC operational Europe area. Height biases of -50 m at 500 hPa were common the

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<sup>1</sup> COAMPS® is a registered trademark of the Naval Research Laboratory.

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wintertime months and much larger than the NOGAPS height biases. Over the past year, a series of real data and simplified tests were run using COAMPS, the results of which motivated the implementation of a new lower boundary condition for the COAMPS nonhydrostatic model.

## *2. Spectral element and discontinuous Galerkin 2D prototypes.*

In FY08 we focused our attention on spectral element (SE) model. The development of the discontinuous Galerkin model is ongoing, led by Frank Giraldo at NPS. We decided to use the same equation set as that used by COAMPS, with the exception that the equations are cast into the flux form. There were three major areas of development: i) implementation of a new lateral boundary condition a simple scalar one-way wave equation (radiation boundary condition), ii) introduction of a passive tracer, iii) introduction of three moisture variables linked with a simple warm-cloud microphysical parameterization. In addition the initialization was modified to allow for vertically non-uniform temperature and humidity. Each new development has been tested on a corresponding idealized case.

## *3. Weighted Essentially Non-Oscillatory (WENO) methods.*

Atmospheric models require numerical methods that can accurately represent the transport of tracers with steep gradients, such as those that occur at cloud boundaries or the edges of chemical plumes. In atmospheric sciences, the most widely used numerical techniques for this type of problem are flux-corrected transport or closely related flux-limiter methods. The limiters are typically designed to prevent the development of new extrema in the concentration field. This will preserve the non-negativity of initially non-negative fields, which is essential for the correct simulation of cloud microphysics or chemical reactions. One serious systematic weakness of flux limiter methods is that they also tend to damp the amplitude of extrema in smooth regions of the flow, such as the trough of a well-resolved sine wave. To avoid this problem, we have been investigating the application of WENO (Weighted Essentially Non-Oscillatory) methods to tracer transport in atmospheric models. WENO methods are widely used in many disciplines, but scarcely been tested in atmospheric applications. WENO methods preserve steep gradients while simultaneously avoiding the dissipation of smooth extrema by estimating the value of the solution in a way that heavily weights the smoothest possible cubic polynomial fit to the local function values. Where the solution is well resolved, all possible cubic interpolants are weighted almost equally. Near a steep gradient, those interpolants are almost completely ignored.

## *4. Accurate microphysical collection rates*

Improvements in the numerical representation of the cloud microphysical processes have been implemented. The changes include the computation of accurate and efficient look-up tables for all nine liquid-liquid and ice-liquid collection processes currently handled in the model. Accuracy is improved by including the numerical bounding technique described by Gaudet and Schmidt (2007) and through the use of digitized variable drop-drop, drop-crystal, and drop-graupel collection efficiencies as computed numerically by Pinsky et al 2001, Wang and Ji 2000; and Khain et al. 2001. The numerical bounding technique will be particularly useful for the envisioned use of semi-Lagrangian techniques as it helps preserve the accuracy of the discretized microphysical collection equations on larger time steps.

# **RESULTS**

## *1. New lower boundary condition for the COAMPS dynamical core*

During FY08, a series of real data and simplified tests were run using COAMPS in order to determine the source of a geopotential height bias. After a series of intensive sensitivity tests, it was determined

that the formulation of the lower boundary condition for the vertical velocity equation was the cause of the geopotential height bias. Three different formulations were tested for the lower boundary condition. A second order finite difference technique was found to produce the best results with the lowest height bias statistics. The new lower boundary condition was transitioned to the operational COAMPS system at FNMOC including the COAMPS-OS system. The mean 500-hPa RMS error and bias statistics for the operational system for December 2006 and 2007 is shown in Fig. 1. The change was made in the operational system just prior to December 2007. A large reduction in the RMS error and bias is apparent due to the new lower boundary condition. Additionally, the sea level pressure bias is reduced at the 72-h forecast time by 80% and the RMS error is reduced by 35%, as shown in Fig. 2.

## 2. Spectral element 2D prototypes.

A radiation lateral boundary condition was developed, implemented, and tested on a linear, hydrostatic mountain wave case for the isothermal atmosphere. The new solution shows improvement over the default lateral sponge layer, especially by removing the noise in the vicinity of the lateral boundaries (Fig. 3). A new passive tracer developed in this project was tested on a simple advection case. The initial tracer concentration retains its shape and magnitude, successfully leaving the domain at the out-flow boundary (Fig. 4). The advection scheme in the existing code is not monotonicity preserving thus negative concentrations with a relative magnitude on the order of  $O(10^{-3})$  appear around the advected passive tracer. The new ‘moist’ spectral element code was tested using a well documented 2D squall line. The initial stratification of temperature and humidity is perturbed by a warm bubble, triggering the convection. Twenty minutes into the integration a well developed deep convective cloud with an updraft transporting moisture rich air from the lower levels produces rain (Fig. 5).

## 3. Weighted Essentially Non-Oscillatory (WENO) methods

We have developing a new method, in which WENO like criteria for the presence of poorly resolved steep gradients are evaluated in a highly efficient manner and used to determine whether spurious new maxima and minima are likely to be created in the vicinity of a steep gradient. This new approach, which we call "selective limiting," can be applied to both flux-corrected transport (FCT) methodologies or to piecewise polynomial approximations for the fluxes in finite-volume methods, particularly the piecewise parabolic (PPM) or cubic methods (PCM). Over a wide range of tests, these schemes were found to give more accurate solutions than WENO methods for considerably less computational cost. A journal paper has been completed (Blossey and Durran, 2008) describing the selective limiting approach and published it in the *Journal of Computational Physics*. We then turned our focus integrating our new method into the COAMPS model and testing it in a variety of situations. These tests are still underway, but one interesting example is shown in Fig. 6.

The test case in Fig. 6 is based on Straka et al (1993) and has been proposed as a part of a set of standard test problems for numerical weather prediction models by Bill Skamarock (see [www.mmm.ucar.edu/projects/srnwp\\_tests/index.html](http://www.mmm.ucar.edu/projects/srnwp_tests/index.html)). A cold bubble with a central temperature perturbation of -15K is introduced in a stationary, neutrally stable background with a uniform potential temperature of 300K. The bubble, initially centered at a height of 3km, sinks rapidly and then spreads laterally after reaching the surface, forming a gravity current. Figure 6 shows the potential temperature field after 15 minutes in a two-dimensional simulation as computed using COAMPS with the previously implemented 4th-order leapfrog, the 3rd- and 5th-order Bott scheme options, and with our new selective limiter. Only the right half of the solution is shown in Fig. 6, the perturbations are symmetric about  $x=0$ . In our test the physical diffusivity is  $15 \text{ m}^2 \text{ s}^{-1}$ , which is 1/5 the value used in Straka et al (1993) and in the tests on Skamarock's webpage. We use a lower value of physical diffusion to reveal

the capabilities of each scheme to accurately simulate the poorly resolved filaments of perturbation potential temperature. The rollup of vortices along the top of the gravity current and filamentary structures are clearly visible in Fig. 6. We are currently obtaining a converged, high-resolution solution against which these results can be compared, but we note that the selective result appears to provide a better representation of the filaments than the Bott solutions, and of course better than the leapfrog result.

At present the leapfrog solution requires a smaller time step than the other methods, has more non-physical oscillations despite having a larger effective diffusivity (due to the smaller time step) and is much slower. The relative timings for the Bott 3rd/Bott 5th/Selective methods are in the ratio 6/8/7, implying that our new method is faster than the 5th-order Bott scheme, but slower than the 3rd-order scheme. However, a significant advantage of our new method is that it can be used with much larger time steps in semi-Lagrangian simulations and could therefore be used to model tracer transport much more efficiently than the methods currently available in COAMPS---provided COAMPS is modified to allow passive tracers to be integrated on longer time steps than those used for the dynamics.

#### *4. Microphysics Development*

An important aspect of any cloud microphysical scheme is an accurate representation of the mass transfer rates between the various condensate categories of which the scheme is comprised. Within convective-scale updrafts, for example, a rapid transfer of liquid to the fast (graupel) or slower falling (snow and ice) categories will impact both the thermodynamics and loading terms affecting updraft maintenance or demise as well as the generation of long-lived convective-induced anvil clouds. One such conversion term that has an important role in the formation of faster falling graupel particles is the collection of rain drops by snow particles at temperatures below 273.0K. The accuracy of standard time discretization of this particular microphysical collection rate is demonstrated in Fig. 7. In this example we are computing the fractional depletion of rain during a time step by a fixed amount of snow (in this example the snow mixing ratio is set to 2.0 g/kg). The solid curves in the plot represent the fractional depletion as computed by the standard time discretization of the bulk collection rates for three typical mesoscale time steps that would likely be encountered in our standard operational runs. What becomes evident from inspection of this Figure is that the snow-rain interaction acts as a complete sink of rain for nearly the entire spectrum of rain mixing ratio evaluated even when the time step is as low as 5 seconds. This would lead to rapid freezing of the rain at the first grid point just above the melting level. Taking larger time steps leads to a difference in the collection rate of nearly two orders of magnitude over that obtained through the numerical bounding technique (dashed lines). Further, it is evident that the numerical bounding technique gradually reaches, but does not exceed, the limit of complete depletion as the time step is increased. This allows the parameterizations to perform over a much larger time-step without the need to introduce artificial limits to the growth rates commonly applied to prevent over-depletion and the development of negative values in the microphysical scalar fields. Further refinements to the rate calculations are incorporated through the use of variable collection efficiencies during the numerical integration of the collection rates.

## **IMPACT/APPLICATIONS**

COAMPS is the Navy's operational mesoscale NWP system and is recognized as the key model component driving a variety of DoD tactical decision aids. Accurate mesoscale prediction is considered an indispensable capability for defense and civilian applications. Skillful COAMPS predictions at resolutions less than 1 km will establish new capabilities for the support of the warfighter and Sea Power 21.

Operational difficulties with weapon systems such as the Joint Standoff Weapon (JSOW) have been documented in regions with fine-scale topography due to low-level wind shear and turbulence. Improved high-resolution predictive capabilities will help to mitigate these problems and introduce potentially significant cost saving measures for the operational application of JSOW. The capability to predict the atmosphere at very high resolution will further the Navy sea strike and sea shield operations, provide improved representation of aerosol transport, and will lead to tactical model improvements. Emergency response capabilities and Homeland Security issues within the DoD and elsewhere, such as LLNL, will be enhanced with the new modeling capability.

## TRANSITIONS

The next generation COAMPS system will transition to 6.4 projects within PE 0603207N (SPAWAR, PMW-180) that focus on the transition COAMPS to FNMOC. The improvements to the COAMPS dynamical core have been transitioned to the SPAWAR 6.4 project and subsequently to operations as a result of the marked improvement in the geopotential height bias statistics.

## RELATED PROJECTS

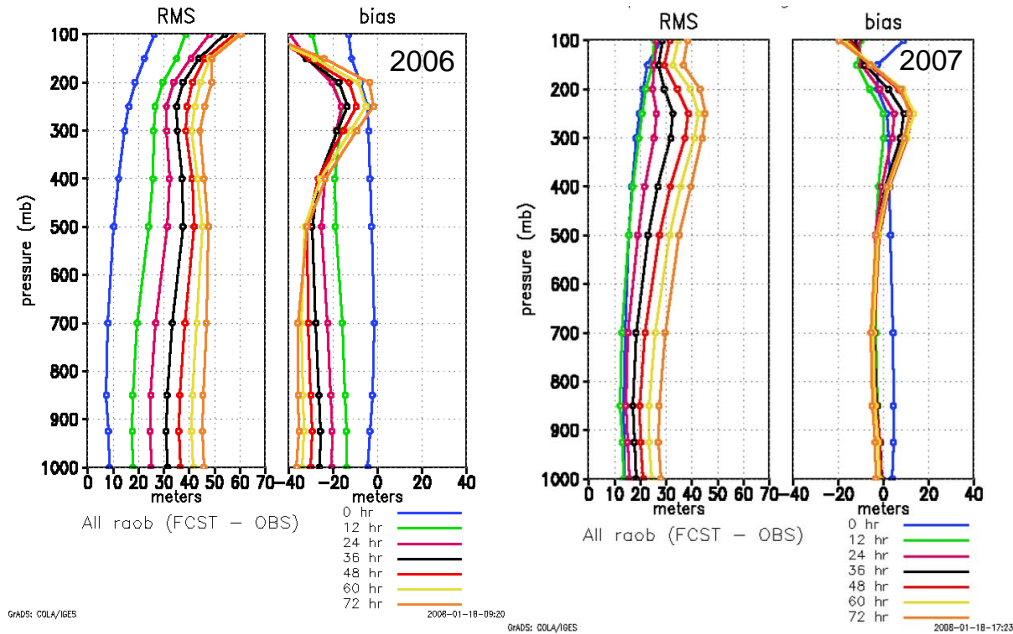
COAMPS will be used in related 6.1 projects within PE 0601153N that include studies of air-ocean coupling, boundary layer studies, and topographic flows and in related 6.2 projects within PE 0602435N that focus on the development of the atmospheric components (QC, analysis, initialization, and forecast model) of COAMPS. .

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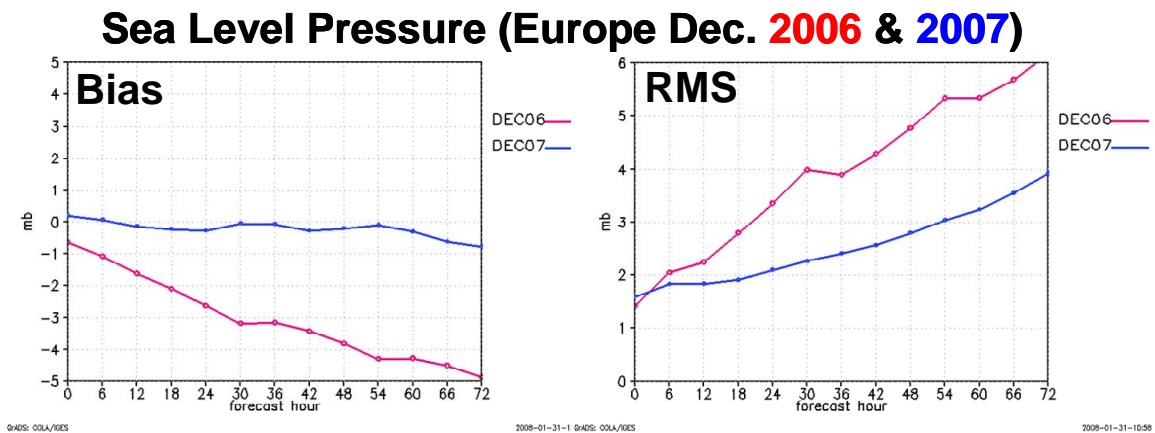
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## PUBLICATIONS

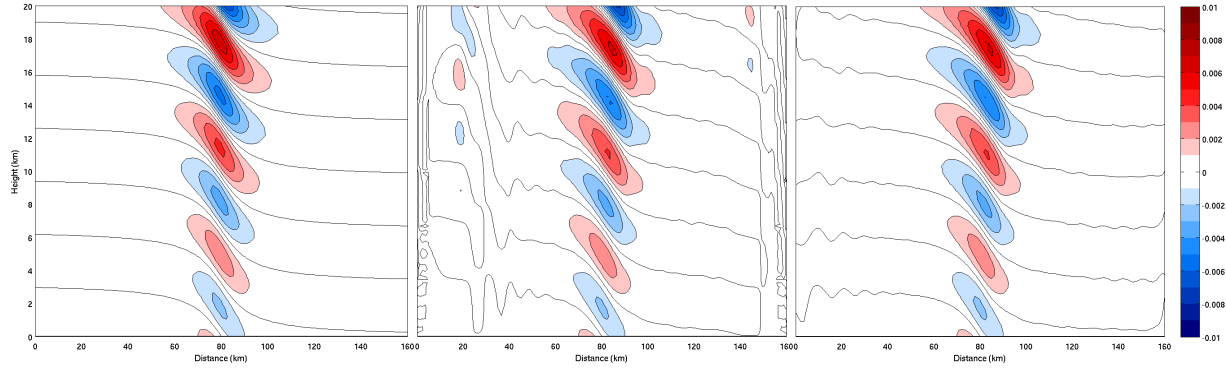
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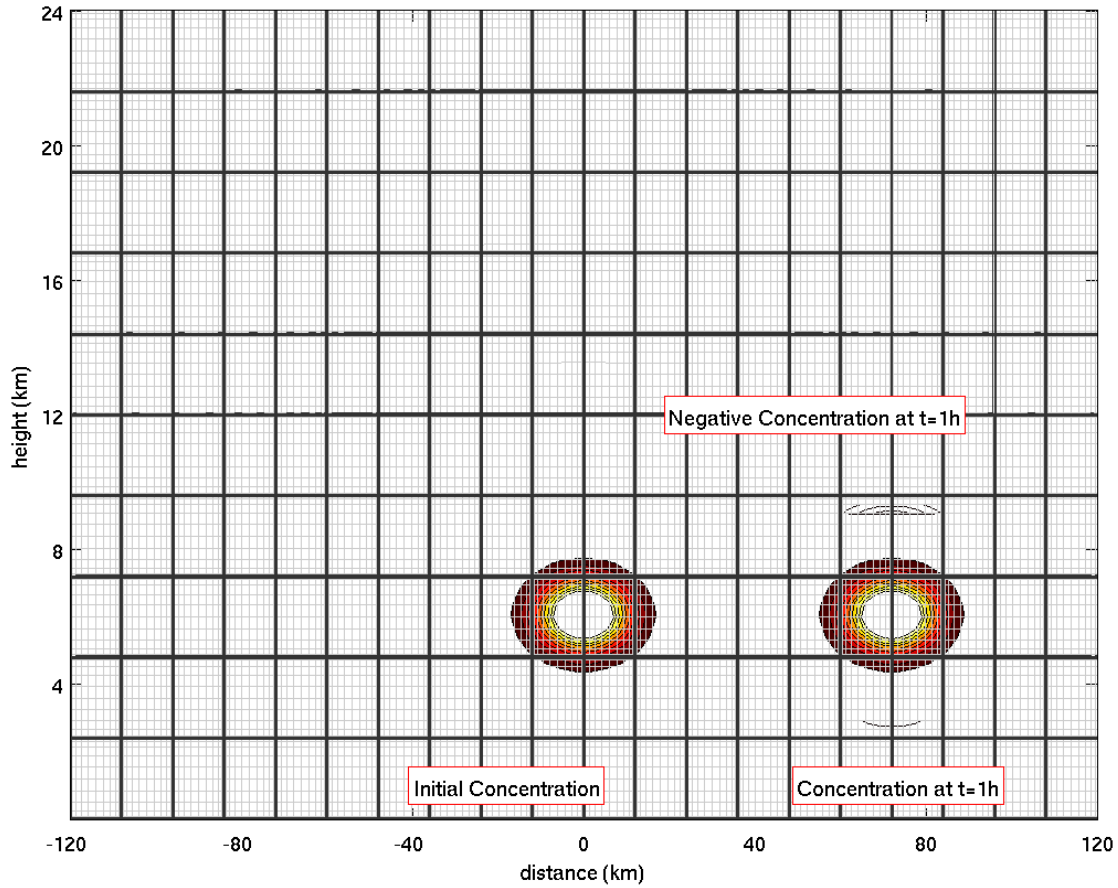
**Figure 1.** Geopotential height RMS error and bias statistics for 2006 (left) and 2007 (right) for the COAMPS operational area over Europe. The new boundary condition in the dynamical core was implemented for the December 2007 forecasts.



**Figure 2.** Sea level pressure bias (left) and RMS (right) error statistics for 2006 (red) and 2007 (blue) for the COAMPS operational area over Europe. The new boundary condition in the dynamical core was implemented for the December 2007 forecasts.

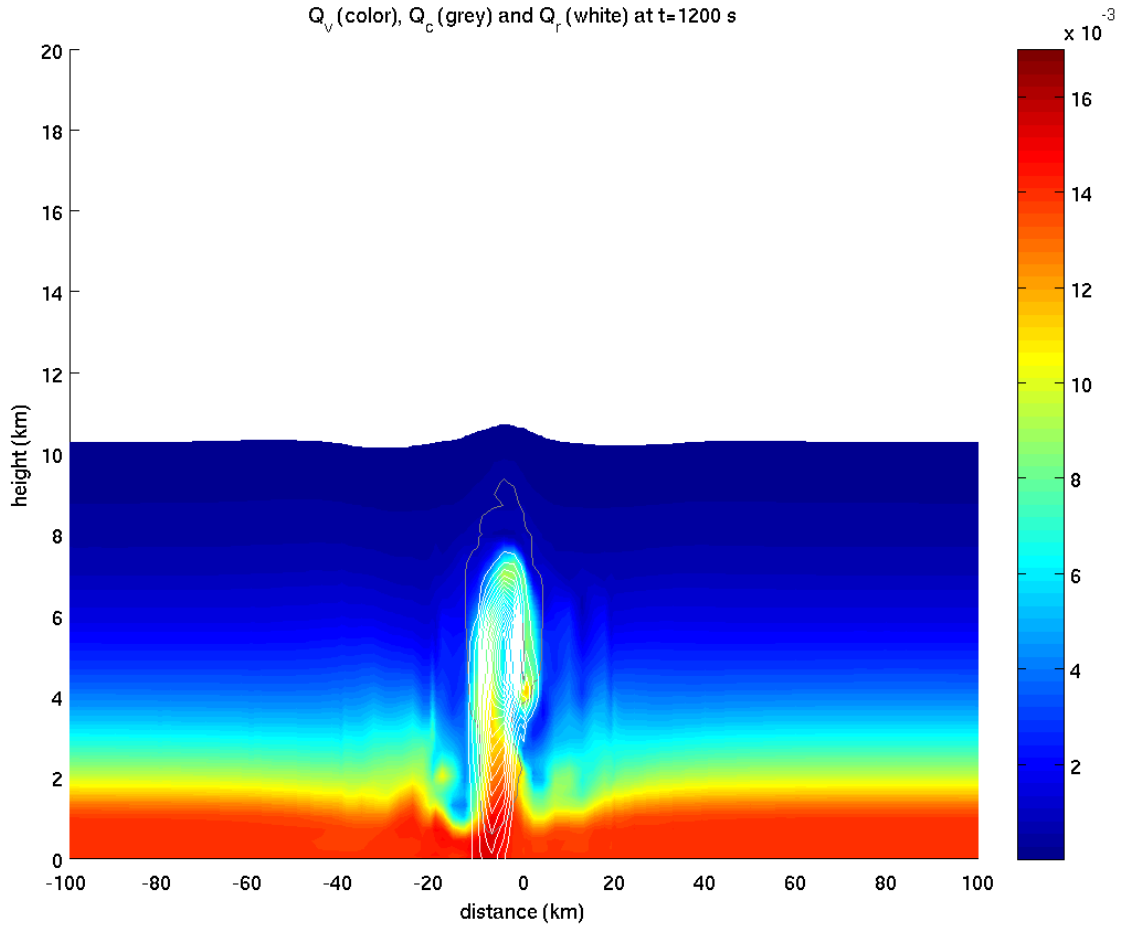


**Figure 3.** Vertical wind velocity for the linear, hydrostatic mountain case: exact solution (left), original sponge lateral boundary condition (center) and new radiation lateral boundary condition (right).

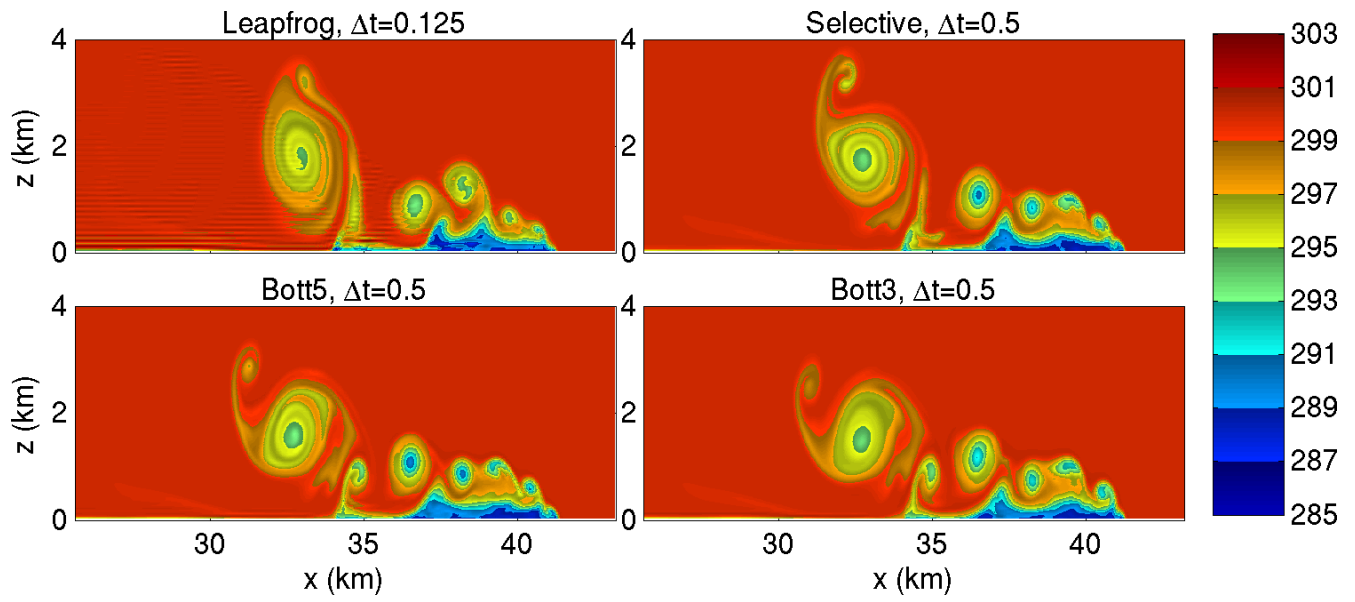


**Figure 4.** Passive tracer advection: Concentrations at  $t=0$  and  $t=1$  h. Note appearing lobes of negative concentration at  $t=1$  h. Element structure with nodal lines are superimposed.

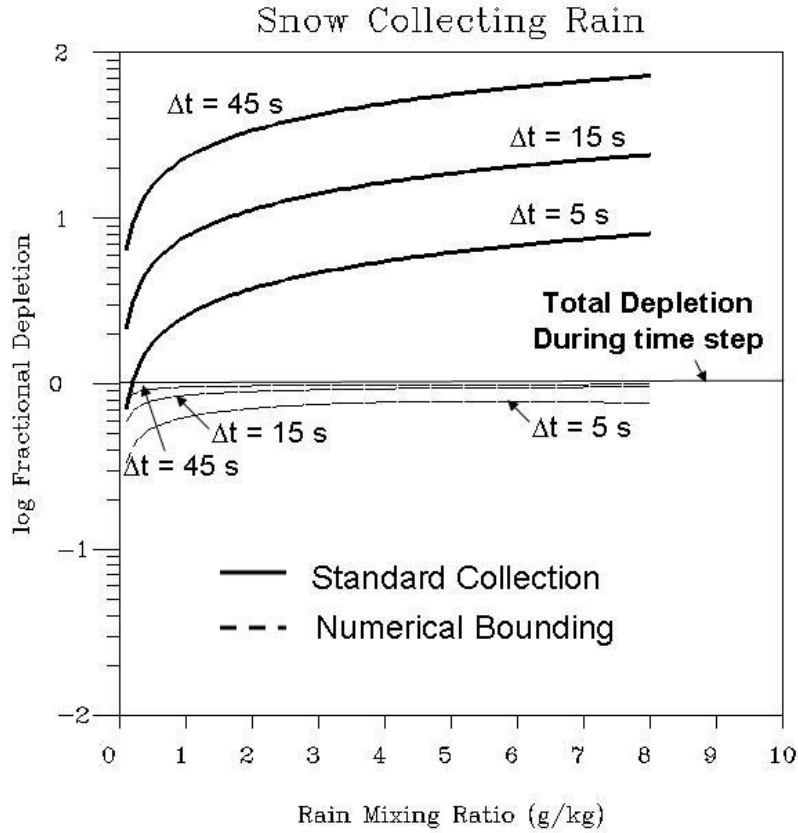




***Figure 5. 2D squall line experiment using the spectral element model after 20 minutes of integration. The colored field represents the water vapor mixing ratio, the grey contour outlines the cloud by using a single value of the cloud water mixing ratio and the white contours represent rain water mixing ratio.***



**Figure 6.** *The potential temperature field after 15 minutes in a two-dimensional simulation as computed using COAMPS with the previously implemented 4th-order leapfrog (upper left), the 3rd- and 5th-order Bott scheme options (bottom), and with our new selective limiter (upper right).*



**Figure 7. The log of the fractional depletion of rain mixing ratio by a fixed value of the snow (2 g/kg).**

*The solid curves represent the fraction depletion rate as computed by a standard time discretization of the bulk microphysical collection equation. The thin dashed lines represent the fraction depletion using the numerical bounding technique described by Gaudet and Schmidt (2007). The three labeled solid and dashed curves represent various time steps typical of high-resolution operational mesoscale grids. A total fraction depletion value of log (1.0) is denoted by the thin solid line. Values above this limit would generate negative condensate values during the time step unless artificial limits are imposed.*